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Fig 1

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Fig   2

Fig   3

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Fig 4

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120

estimate of
$(n_{775nm}L)_{measured}$
based on $S_{fringe}*$

possible values of
$(n_{775nm}L)_{measured}$
based on $S_{phase}*$

correct estimate of
$(n_{775nm}L)_{measured}*$

122

26.7

25.111   26.111   27.111   28.111

25   26   27   28

Fig 5

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START

124

Placing sample interfaces as the end
reflectors of a signal interferometer
arm
126

Scanning the reference mirror in the
reference interferometer arm
128

Combining the reflections from the
signal and reference arms and
separating them by wavelength
130

Detecting the heterodyne
oscillations in the intensities of the
combined light
132

Extracting the phases of the
heterodyne signals
134

Evaluating a difference phase for
the entire scan
136

Repeating the scan with the
wavelength of the light being
slightly detuned
137

To Fig. 6B

Fig 6A

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From Fig   6A

Superposing the two difference
phases found from the two scans   138

Determining the locations of the
sample interfaces by the phase
crossing points   140

Determining the optical separation
between the interfaces by counting
the number of times the heterodyne
signal associated with the CW light
wraps over by 2π between the two
crossing points   142

Refining the separation distance by
measuring the difference phase at
the crossing points   144

END

Fig   6B

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Fig 7

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START

/ 184

Placing sample interfaces as the end reflectors of a signal interferometer arm — 186

Scanning the reference mirror in the reference interferometer arm — 188

Combining the reflections from the signal and reference arms and separating them by wavelength — 190

Further separating the LC wavelength with filters

Detecting the heterodyne oscillations in the intensities of the combined light — 196

Detecting the heterodyne oscillations with three detectors

Extracting the phases of the heterodyne signals — 198

Evaluating a difference phase for each LC signal with the CW signal — 200

To Fig. 8B

Fig 8A

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From Fig   8A

Superposing the two difference phases — 202

Determining the locations of the sample interfaces by the phase crossing points — 204

Determining the optical separation between the interfaces by counting the number of times the heterodyne signal associated with the CW light wraps over by 2π between the two crossing points — 206

Refining the separation distance by measuring the difference phase at the crossing points — 208

END

Fig   8B

approximately harmonically
related low coherence, λ_1,
and CW, λ_2, light beam

256

251

262

detector for λ_2

260

dichroic — 258
mirror

computer or
processing
unit

264

detector for λ_1

263

252

254

target

268
lenses

266
reference
mirror

250

Fig 9

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270

phase crossing system
using low coherence
500 nm and 1000 nm
CW light

272

274

phase crossing system
using low coherence
900 nm and 1800 nm
CW light

276

278

Fig   10

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300

M 306

308
PM

laser 304 310
302 MM
BS fast slow

S + ← LO
312 320

318
D

322 LO → MX → feedback
314
MX electronics
316

Display
317

COMPUTER
315

Fig. 11

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350

M

356

352 355   358
laser   PM   360
355   MM
353   354   fast   slow
LC source   BS

M   LC   362   S (+) ← LO   376   375
364   DBS   Display
             laser

             D 366

LO → ⊗ →   feedback   372   Computer
370   MX   electronics   373

LO 384   sample on coverslip

⊗ ← ◁ ← BS

sample   380 L   382
phase   386   d
signal

Fig   12

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400

-2nd

+2nd

ΔL

Fig 13

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420

d

sample on coverslip
430

L
428

426   432
LC1 422   PM
LC2 424   BS   MM
                                 434
                          fast   slow
LO 440   454
           LC2   S (+) ← LO
           436   456
⊗ ← ◁ ←   DBS
           438   LC1
                      444

sample
phase
signal
442   455

                      D 446

448   452   DISPLAY
LO → ⊗
450 MX   feedback
          electronics   COMPUTER

                                453

Fig. 14A

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458

459

Cells

Mirror for 633nm
460

473

4 lenses

469

475

471

633nm
845nm

0 ⊕ ⊕ PZT driver

462
BS

463

$A\sin(\delta\phi+\theta)$ Synthesizer(f)

Mirror
with PZT
461

468

$AJ_1\sin(\delta\phi)$ ⊗

$\cos(\theta)/J_1$

465

633nm

DM
464
845nm

PD

+

467

$\sin(\theta)/J_2$ x2

$AJ_2\cos(\delta\phi)$ ⊗

CCD
466

479

DISPLAY

Fig 14B

CCD
CONTROLLER   477

COMPUTER

478

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470

LC2

ΔL

Fig. 15A

LC1

ΔL

Fig. 15B

480

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500

sample on coverslip

d

f_2

508

f_1

LC1

502

506

510

PM

f_2

512

MM

LC2

504

BS

f_1

514

fast

slow

532

S

LO

530

516

LC2

DBS

518

LC1

520

CCD or
PD array

524

D

522

526

LO

MX

528

feedback
electronics

Display

525

Computer

523

Fig 16

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Fig 17

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580

objective
40x   tube lens

HeNe laser   584   586

582

Acousto-optic
frequency
Shifters 594   Beam expander
Δf = 100 kHz

588

sample

592

570

604

598   600   PD 1

Mirror
on PZT   596   602   PD 2   668

MM fiber   Phase
detector

606

609

PROCESSING
DEVICE

611

DISPLAY

Fig   18A

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670

HeNe laser EOM

671

672

Acousto-optic frequency Shifters
$\Delta f = 100$ kHz

677

Mirror on PZT

678

Beam expander

679

680

682 CCD

681 polarizer

PD 1

683

684 CCD CONTROLLER

685 COMPUTER

686 DISPLAY

673

674

sample

objective 40x

tube lens

675

676

Fig. 18B

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Heterodyne signal I₁

0 phase shift

π/2

π

3π/2

687

688

689

690

691

Gating signals

Fig. 18 C

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Fig. 18D

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Fig. 19

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700

Fig. 20

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Fig. 21

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820

822

804   826

$$I_1(t) = \cos(\Omega t + \phi_1 - \phi_1')$$
$$I_2(t) = \cos(\Omega t + \phi_2 - \phi_2')$$

ϕ_2 ϕ_1

ϕ_2' ϕ_1'

Fig   22

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Fig 23A

PZT Voltage

840

Phase change (1550nm)

850

Fig 23B

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$\S$ 860

Fig. 24

beamsplitter

$\S$ 880

signal

882

884

Mirror on PZT

886

888

Fig. 25 A

$\S$ 900

reference

902

904

glass

Fig. 25 B

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FIG. 26

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980

Fiber end — 984

986

988

Reference glass

stimulation
electrodes 996a

recording
electrodes 998a

990

996b

998b

saline in wells 994

Nerve bundle 992

FIG. 27

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$\} 1000$

FIG. 28A

$\} 1006$

FIG. 28B

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1010

FIG. 29

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FIG. 30

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1070

FIG. 31

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FIG. 32B

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FIG. 33

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FIG. 34

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FIG. 35

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$\int_L 2080$

FIG. 36

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2090

2100

FIG. 37

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FIG. 38

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FIG. 39

Objective focus position

Backreflected intensity

Axial rays   Marginal rays

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FIG. 40

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marginal rays
front surface

marginal rays
back surface
& axial rays
front surface

axial rays
back surface

Backreflected intensity

Objective focus position

FIG. 41

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FIG. 42B

FIG. 42A

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2380

Overall diameter 2.5 mm

GRIN lens: 2mm diameter,
4mm length, 0.25mm WD

Sample
2388

2390

2384
housing

2382
Fiber pigtailed
collimator

Reference surface from
2386 uncoated rear surface of
GRIN lens

FIG. 43

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2400

Dual-beam probe applied to nerve experiment

2406

2402

2408

2404

FIG. 44

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2450

2452

2456

PZT
translator
2454

FIG. 45

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FIG. 46A

FIG. 46B

FIG. 46C

2460

2470

2480

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2484

PCX lens f=25mm

2485

2486 coverslip

FIG. 46E

2482

FIG. 46.D

2487

2488

FIG. 46G

Unwrapped phase

position, microns

FIG. 46F

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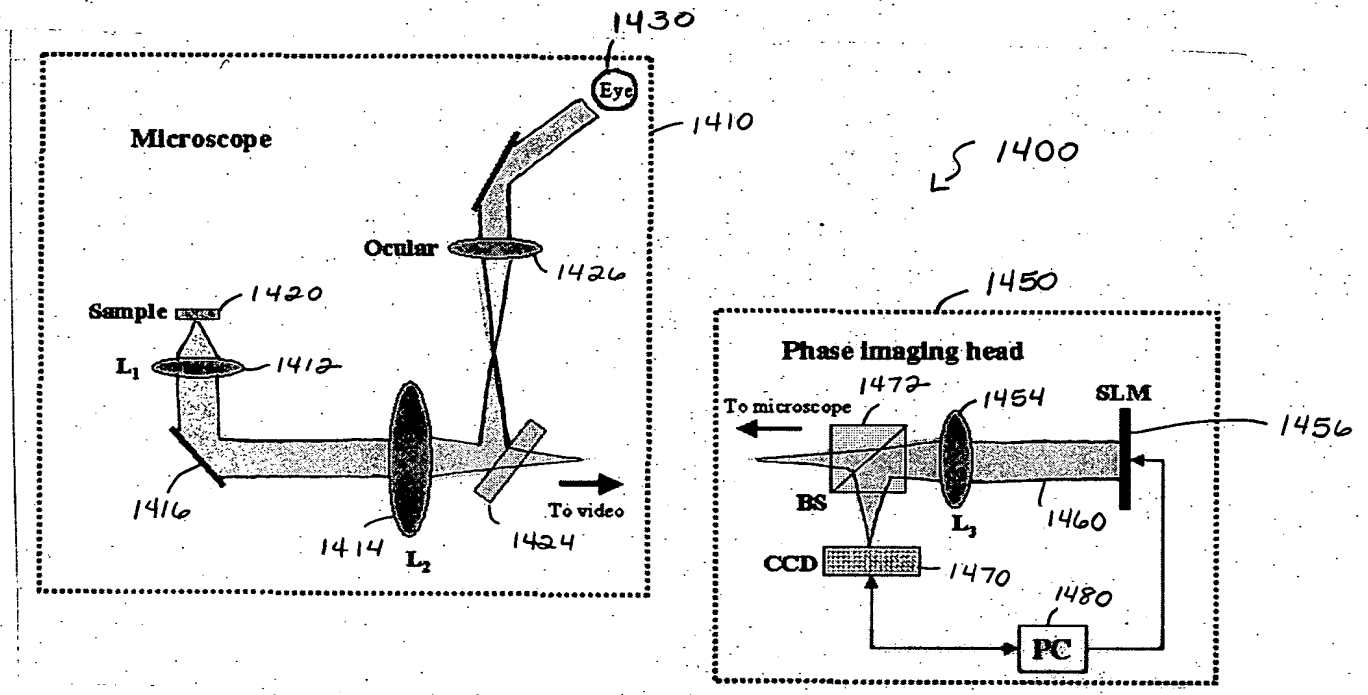Inventors: Christopher M. Fang-Yen et al.
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2490

2494 TEST

SOURCE 2492

REF 2498

INTERFEROGRAM 2496

1) MODULATE PHASE

2) RECORD MIN 3 FRAMES

3) CALCULATE OPD

$$OPD = \frac{\lambda}{2\pi} \, TAN^{-1} \left[\frac{C-B}{A-B} \right]$$

A 0° B 90° C 180°

FIG. 47A

2500

2510

Phase stepping

2500

MIRROR POSITION

λ/2 λ/4

A B C D

TIME

FIG. 47B

DETECTED SIGNAL

A B C D

0 π/2 π 3π/2 2π

PHASE SHIFT

FIG. 47C

Bucket integration

2520

MIRROR POSITION

λ/2 λ/4

A B C D

TIME

FIG. 47D

2530

DETECTED SIGNAL

A B C D

0 π/2 π 3π/2 2π

PHASE SHIFT

FIG. 47E

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2560

DETECTED SIGNAL

A B C D

0 π/2 π 3π/2 2π

PHASE SHIFT

FIG. 48C

2550

MIRROR POSITION

λ/2

λ/4

A B C D

TIME

FIG. 48B

Bucket integration

2540

FIG. 48A

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Blue = illumination +
reference

Red = scattered light from
sample

FIG. 49

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2600

FIG. 50A

2620

FIG. 50B.

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1100

1104

1106 1102

FIG. 51A

1114

1106

1112

FIG. 51B

1124 1120

1126

1122

FIG. 51C

1126

1134 1130

1132

FIG. 51D

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FIG. 5a

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FIG. 53

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FIG. 54A

FIG. 54B

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FIG. 55

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1600

Scope — 1674

PC 2 — 1672

1632

1660

1658

SLM

P_c

1656

1662

Detector — 1664

L_3 1634

1630

1640

········ Calibration
——— Imaging

P

CCD

1636

1612

1654

1640

FIG. 56

BS

1638

1652

1606

L_2

L_1 1604

Sample

PC 1

1670

1613

1626

BS

1622

FC

1614

1616

HeNe

1620

SLD

1624

1610

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S

1702

E_i

1704

f

1706

1700

FIG. 51A

1750

S

1754

1752

E_i

f

1756

FIG 51B

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Operation

RGB $\xrightarrow{}$ 1802

Voltage 1804

Phase 1806

1800

FIG. 58 A

Calibration- amplitude mode

I(gray scale) 1852

ϕ(gray scale) 1854

1850

FIG 58 B

Control- phase mode

gray scale 1856

ϕ 1858

1855

FIG. 58 C

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FIG 59

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4-frame sequence

Magnification 13X

FIG 60A

2000

FIG 60B

2200

FIG 60C

2400

FIG 60D

2600

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Phase between E_H and E_L

φ is the "real" phase

FIG. 21

2100

E_H

2104

$\Delta\varphi$

E

2102

φ

E_L

2106

2112

2110

FIG. 22

2200

2202

2204

2206

Delta-phi Unwraped

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FIG. 63

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266 nm expected

10 micron grooves
Magnification 50X

FIG. 24

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Onion Cells

Magnification 50X

Phase image 2550

FIG. 66

Microscope (intensity) image 2500

FIG. 65

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FIG 67

FIG 68A   FIG 68B

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FIG. 69 A

FIG. 69 B

FIG. 69. C